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14. ABSTRACT
A novel approach for increasing the system-level efficiency of a thermoelectric generator (TEG) by utilizing convective heat transfer from the cold side of the generator to hot one will be explored. Existing theoretical framework will be expanded to include the physical detail of concrete experimental systems. Demonstration devices will be designed and built. Test and measurement setup for model validation will be constructed. Power generation efficiencies of the convective TEG will be measured and compared to operation without convection. It is expected that by using the convective heat transfer the efficiency of TEG can be increased by 12% to 18% for metallic TE elements, such as copper-constantane couples, and by 18% to 32% for higher performance semiconductor TE materials. Conventional and advanced thermoelectric materials will be used for generator construction. Thick film nanostructured TE materials from UCSB and/or MIT/LL will be used to construct convective TEG modules if they become available.

15. SUBJECT TERMS
Thermoelectrics, thermoelectric power generation, convective heat transfer to improve system efficiency of a thermoelectric generator

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Final Report
Increased Efficiency
Thermoelectric Generator With Convective Heat Transport
25 February 2011

Contract Information

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Title of Research	Increased Efficiency Thermoelectric Generator With Convective Heat Transport
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Technical Section

Abstract

A novel approach for increasing the system-level efficiency of a thermoelectric generator (TEG) by utilizing convective heat transfer from the cold side of the generator to hot one will be explored. Existing theoretical framework will be expanded to include the physical detail of concrete experimental systems. Demonstration devices will be designed and built. Test and measurement setup for model validation will be constructed. Power generation efficiencies of the convective TEG will be measured and compared to operation without convection. It is expected that by using the convective heat transfer the efficiency of TEG can be increased by 12% to 18% for metallic TE elements, such as copper-constantane couples, and by 18% to 32% for higher performance semiconductor TE materials. Conventional and advanced thermoelectric materials will be used for generator construction. Thick film nanostructured TE materials from UCSB and/or MIT/LL will be used to construct convective TEG modules if they become available. The architecture of the convective TEG is inherently advantageous for utilization of these thick film advanced TE materials as this kind of TEG benefits from high aspect ratio, thin TE materials operated in an in-plane geometry. [Thick film TE materials did not become available during the conduct of this project. Therefore, no second set of TE modules using thick film were constructed or tested.]

Technical Objectives

The purpose of this project is to explore an approach for increasing the system-level efficiency of a thermoelectric generator (TEG) by utilizing convective heat transfer from the cold side of the generator to the hot side, recovering conductive heat loss. The specific project objectives are to

1) Develop and test a convective TEG, incorporating metallic thermoelectric elements, that increases TEG power generation from that of a conventional TEG by 12 – 18%.

2) Develop and test a convective TEG, incorporating nanostructured thick film TE elements, that increases TEG power generation from that of a conventional TEG by 18 – 32%.

Technical Approach

Background

Recent advancements in TE materials (Ref. 1,2,3,4, & 5) and systems (Ref. 6,7, & 8) have renewed interest in the technology's potential for waste heat recovery and power generation for both military and commercial applications. Thermoelectric systems deserve special focus because the technology has the prospect of helping reduce dependence on imported fossil fuels and the critical need to reduce CO_2 emissions, two vexing issues the US faces today. However, the adoption of TE technology has been slowed and, in many areas of potential use, prevented, by low efficiency and a resultant relatively small net benefit from usage.

In this project, concepts are presented to improve the system efficiency through a fundamental change to the way TE materials are configured in solid state power conversion systems. The result offers the prospect of increased system level efficiency. Simplified models indicate that efficiency of thermal power conversion could increase by up to about 30%, in systems where the thermal power is contained in a hot gas or liquid stream, over that of any present designs. Efficiencies approach those of thermoelectric systems with infinite heat sinks at both the heat source (hot) and heat sink (cold) ends.

Technical Discussion

This discussion follows a more comprehensive analysis in Ref 8. The basic equation for the efficiency; Φ, of an ideal conventional TE heat engine is;

$$\Phi = \frac{\text{NET ELECTRICAL POWER OUTPUT}}{\text{NET THERMAL POWER INPUT}} = \frac{I^2 R_l}{\alpha\, I T_{HP} - \frac{1}{2} I^2 R_i + K \Delta T_P}$$

Where these terms, equations and figures and those that follow are defined and developed in Ref 8. The first term in the denominator is the reversible Seebeck thermal power input. The second and third terms are, respectively, Joule heating and conductive heat flow. The latter two are the dissipative losses that reduce efficiency below Carnot efficiency in an ideal TE heat engine.

Convection can be used to reduce these irreversible mechanisms (Ref 8, 9, 10), by sweeping the heat content (enthalpy) to, and then out from, the hot side. Equation (2) becomes

$$\eta_C(\delta_P) = \frac{I^2 R_l}{\alpha\, I T_{HP} + \zeta(\delta_P) K \Delta T_P - \frac{\xi(\delta_P)}{2} I^2 R_i}$$

Where δ_p is:

$$\delta_P = -\frac{C_P m \Delta T_C}{K \Delta T_C}$$

It equals the ratio of convective transport to conductive transport. $\xi(\delta_p)$ and $\zeta(\delta_p)$ are the heat transport functions, respectively, for Joule heating and conduction from the hot to cold ends. Figure 1 presents the effect of δ on efficiency for the ideal case. It is readily apparent that the efficiency increases rapidly with δ, and Φ approaches the Carnot limit as δ approaches about 10. To describe accurately the performance of a real TE generator more complex models are required. However, the simplified model does show the

characteristics and functional dependence of efficiency on δ. Preliminary studies indicate that the performance of actual devices will follow the curves for δ up to about 2. Beyond that value, the simplified equation's ignored loss terms can make significant contributions to the results. The calculated efficiency gains will be larger that actual gains by an increasing amount as δ increases beyond 2.

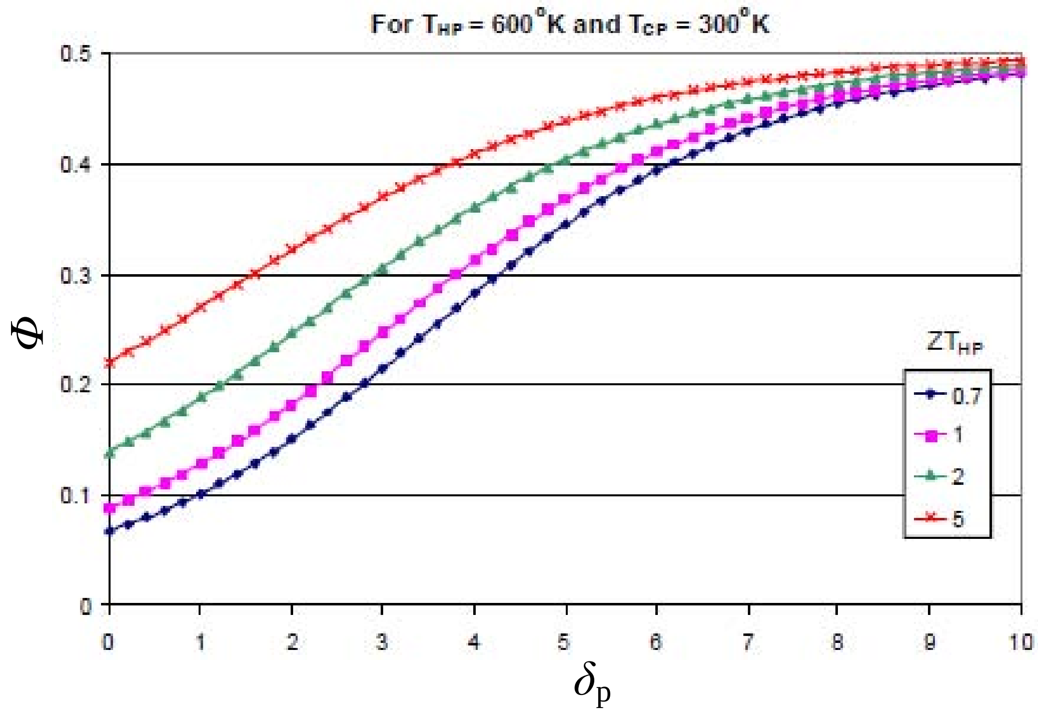

Figure 1. Efficiency as a function of the ratio of convective to conductive heat transfer.

These results (gains) occur in system configurations where the heat convected out the hot side can be used in a second heat engine (a cogeneration system) to produce additional electric power. A simple and quite efficient cogenereation system is shown in Figure 2 in which a traditional TE cascade generator is the second heat engine. The working fluid for the system can be gases such as steam or combustion gases (butane and air) high pressure inert gases (X_eH_e mixtures) and liquids such as oils, NaK, or the like. In Table 1, efficiencies for the cogeneration system are compared to those of a traditional cascade, Figure 3, and the infinite heat sink case, Figure 4,. Efficiencies of real generators will be lower, but should be roughly the same proportions of the ideal devices. The results show that the cogenerator configuration shown in Figure 2 is superior to all but the infinite heat sink case, and thus the cogenerator configuration is well worth further study and development.

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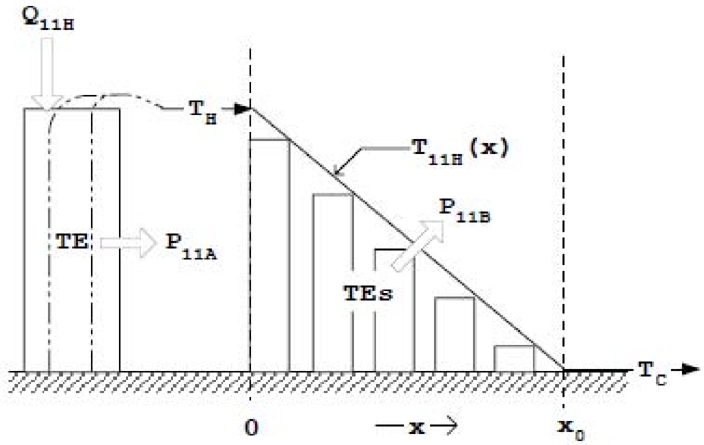

Figure 2. Diagram of a cogeneration system with convective heat transfer.

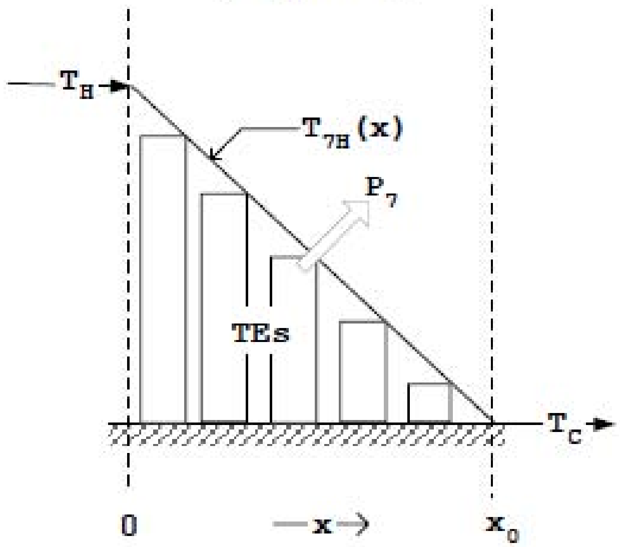

Figure 3. Diagram of a traditional cascade TEG.

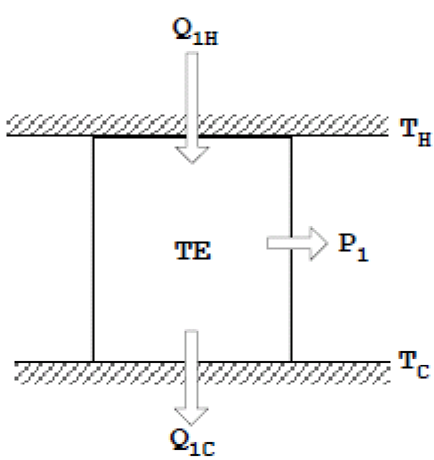

Figure 4. Diagram of a traditional TEG with infinite heat sinks.

	CALCULATED EFFICIENCY, %			
	ZT=1		ZT=2	
CONFIGURATION	T_H=450 K	T_H=600 K	T_H=450 K	T_H=600 K
Infinite heat sinks	5.8	8.9	9.2	15.8
Traditional cascade	3.3	5.4	5.2	8.7
Cogenerator	5.8	8.9	9	13.8

Table 1. TEG efficiency comparison for different TEG configurations.

Experimental Approach

The device model will be used to design a breadboard convective device with an approximately 10mm by 10mm hot side and cold side base dimensions. The initial device will be about 10mm in the direction of heat and convective fluid flow. The material ZT and constituent parameters will be used to predict baseline efficiency and efficiency gains as a function of δ. Initially, the metallic TE material system will be designed, fabricated, and tested to verify the model and measure performance. We expect the performance to follow the characteristic curves of those shown in figure 1, but the quantitative values will be based on our modeling results.

Performance will be measured using thermocouples on the hot and cold sides (to give δ, T, T_h and T_c). Hot side thermal power input will be provided by a high temperature resistor or cartridge heater. The resistor power input will be computed directly from measured DC current and DC voltage inputs. Cold side waste heat flux will be measured using a calibrated flux meter (from known thermal conductance and measured ΔT). Electric power production will be computed directly from DC current and DC voltage outputs. Results will be compared to model predictions and the differences will be rectified. The model and/or experimental setup will be modified as required. Results will be verified through further testing.

The TEG efficiency will be computed using the following equation:

$$\Phi(\delta) = \frac{\text{NET ELECTRICAL POWER OUTPUT}}{\text{NET ELECTRICAL POWER OUTPUT – COLD SIDE WASTE HEAT}}$$

The denominator should also equal the hot side electrical power input (cartridge heaters) minus the heat convected out the hot side in the working fluid. We will compare the two approaches to calculate the denominator of this equation and will rectify any significant discrepancy.

Our initial experiments will use metallic TE elements such as copper-constantane thermocuples. The properties of this material system are well documented. We will etch the desired shapes of the TE elements from thin sheets of parent materials and will join the TE elements by soldering or resistive welding.

We expect the demonstrate efficiency gains of 12% to 18% with the metallic TE material system (percent efficiency gains will be lower at the low ZT of the metal couple, as can be seen from figure 1). Efficiency comparisons for these materials in a standard configuration, the initial tests with metallic materials and the series of tests with UCSB materials will be made. The testing will be conducted by varying the

conductive fluid flow rate. At zero flow, function (and efficiency) will be that of a standard conductive assembly (which we will compute using standard models). Efficiency differences between our convective design and any standard validated design should be minimal, but will be computed and used as a baseline. Measured results will be presented as a function of ΔT.

Upon completion of these tests and availability of UCSB thick film material (75 to 125 micron thickness), the breadboard device will be redesigned to incorporate the UCSB materials and learning from the initial round of testing. The cold and hot side dimensions will be about the same as in the initial design, but the length will be reduced to about 5 mm to compensate for the lower thermal conductivity of the semiconductor TE materials. Measurement methodology will be upgraded if required, but is expected to remain the same as in the initial tests. If UCSB material is delayed or otherwise not available, Lincoln Laboratory material or Marlow Bismuth Telluride materials of comparable thickness will be substituted. We expect the measured efficiency gains to be between 20% and 32% for the UCSB and Lincoln Laboratory materials and 18% to 30% with Marlow materials compared to TEG with no convective heat transfer.

Source of Developmental Materials

A further, and very important practical attribute of the proposed configuration is that the design can utilize TE materials between 75 and 125mm thick, and operate them so that both current and heat flow are in-plane. Thus the design is well suited to use UCSB/UCSC (ref 11) and Lincoln Laboratory (ref 12) materials currently being developed under ONR's sponsorship. It is BSST's intent to augment ONR's funding of Dr. John Bower's group's advanced material development, with BSST non-government R & D funds, for material preparation for this program (see attached commitment letter).

Attributes of the Project

Of great importance is that, for use in combustion or flow systems, the cogenerator configuration should use any TE material in the most efficient manner identified to date. With successful development such systems have the prospect of expanding the usage of power generation materials in the larges possible number of military and commercial markets.

Deliverables

The deliverables of the project were to be a combination of experimental results and hardware. At the end of Year 1 Base Period BSST was to deliver:

- a convective TEG module with metallic TE elements with expected efficiency gains of 12 to 18%;,
- a convective TEG module with nanostructured thick film TE elements (supplied by UCSB or MIT/LL) with expected efficiency gains of 18 to 32%, should materials be available,
- test results for these modules operated in convective and regular (no convection) arrangements,
- comparison with the theory, and
- the final report.

At the end of Year 2 Option Period if exercised BSST was to deliver **[Option Period was not exercised]**:

- a convective TEG module with nanostructured thick film segmented TE elements operating at expanded temperature range,
- test results for this module operated in convective and regular (no convection) arrangements,
- comparison with the theory, and
- the final report.

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11. Zeng, G. et al., “Segmented Power Generator Modules of Bi2Te3 and InGaAlAs Embedded with ErAs Nanoparticles”, Proceedings of the Fall 2007 Material Research Society Meeting, Boston, MA.
12. Harman, T.C. et al. “High Electrical Power Density from PbTe-based Quantum-Dot Superlattice Unicouple Thermoelectric Devices”, Appl.Phys.Lett., 88, pp. 243504.

Summary of Progress Achieved

To demonstrate the use of convective heat transfer from the cold side to the hot side of a thermoelectric generator (TEG) to increase system level efficiency of the TEG, a system model was established and an initial convective TEG design was developed. The model and design were refined based on early testing of a metallic TE couple made of Constantan-Chromel strips, representative of the full TEG design. A convective TEG was then built, tested, and characterized. Based on initial results, additional testing was conducted. Repeatable behavior and influence of convection was observed, captured and quantified. Analysis of these results is presented below. The conclusion reached was that under certain conditions, the use of convective heat transfer provided some benefit to increasing system level efficiency.

Progress Achieved

The initial action taken in this project was to expand BSST’s previously developed theoretical basis for the utilization of convective heat flow to improve TEG system level efficiency. This expansion was incorporated into a developing model of the convective TEG. Based on simulations using this model, the design of the convective TEG demonstrator was established, as presented in Figure 5.

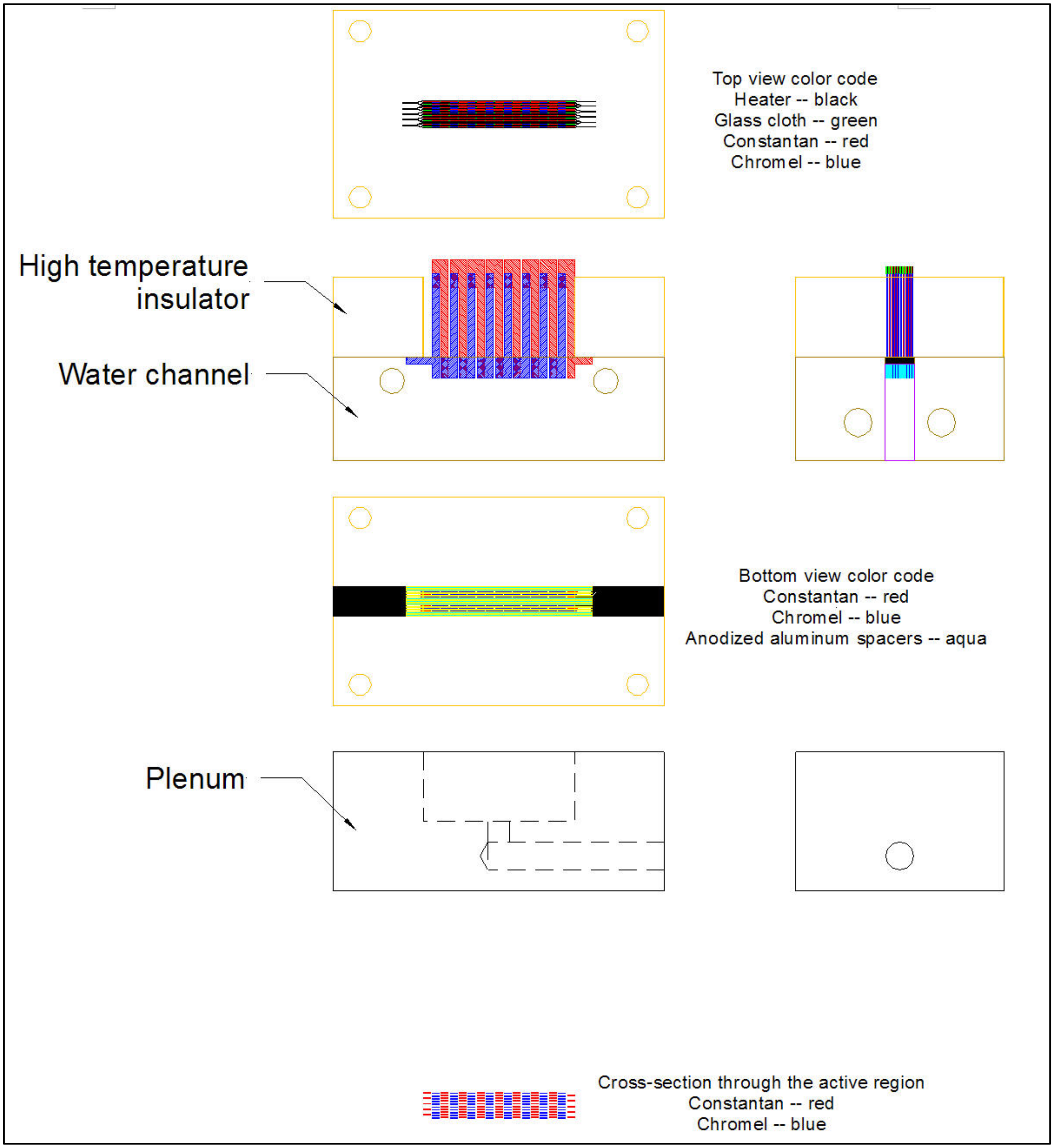

Figure 5. Layout of convective TEG demonstrator.

Following establishment of the convective TEG design, components were fabricated and assembled. Special attention was placed on the method of fabrication and assembly of the strip of metal couples. This strip would eventually consist of the Chromel-Constantan TE couples that would power the TEG. Stainless steel parts were fabricated and used to practice and refine the welding that would be required to assemble the Chromel-Constantan couples once the materials were received. Figures 6 through 10 present various views of the parts as they were initially assembled and validated.

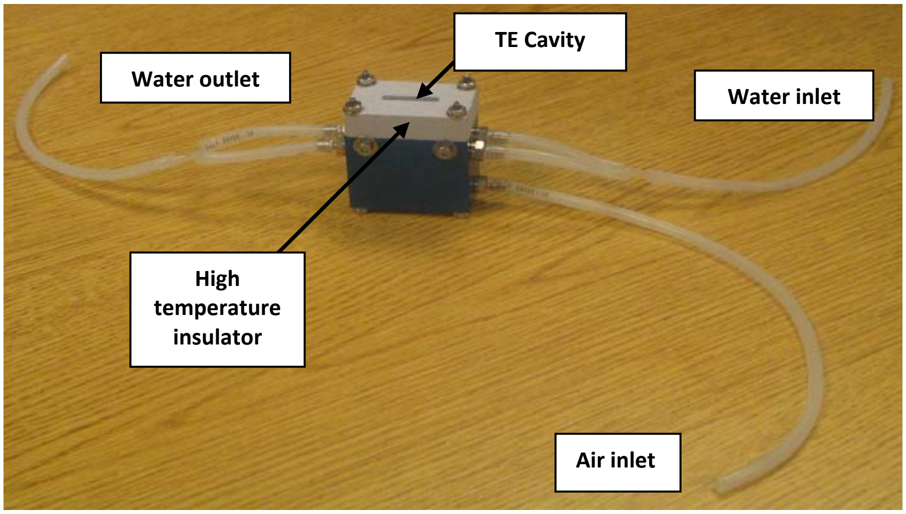

Figure 6. Housing assembly without thermoelectric generator parts.

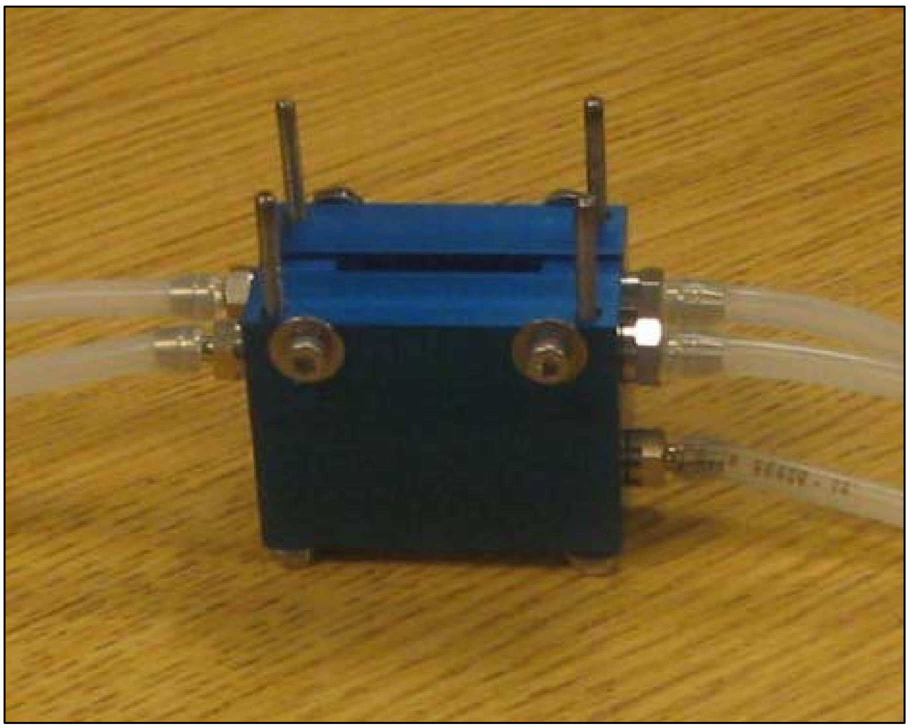

Figure 7. Housing assembly with high temperature insulation removed.

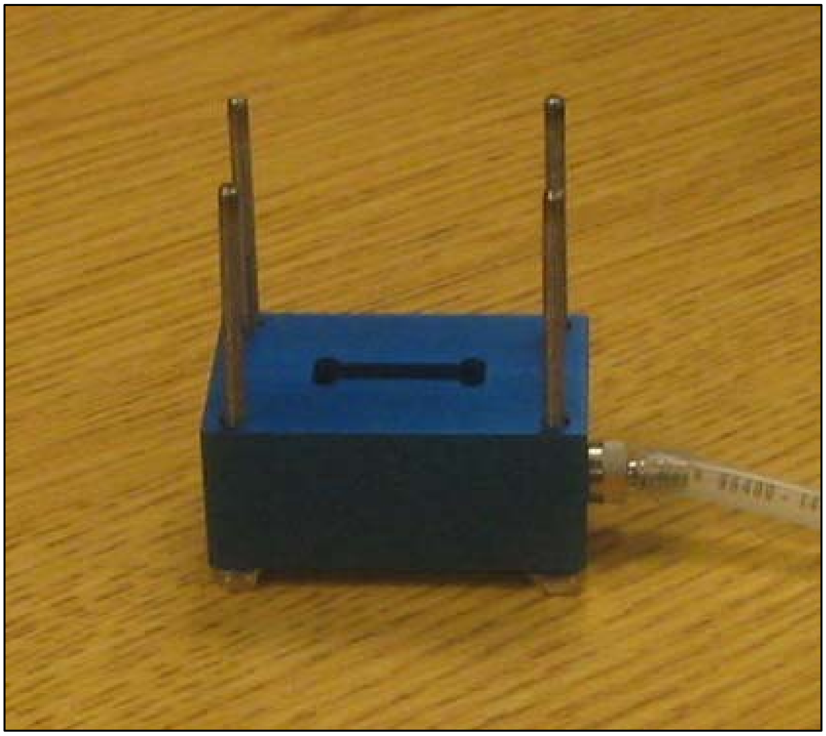

Figure 8. **Housing assembly with the air plenum layer only.**

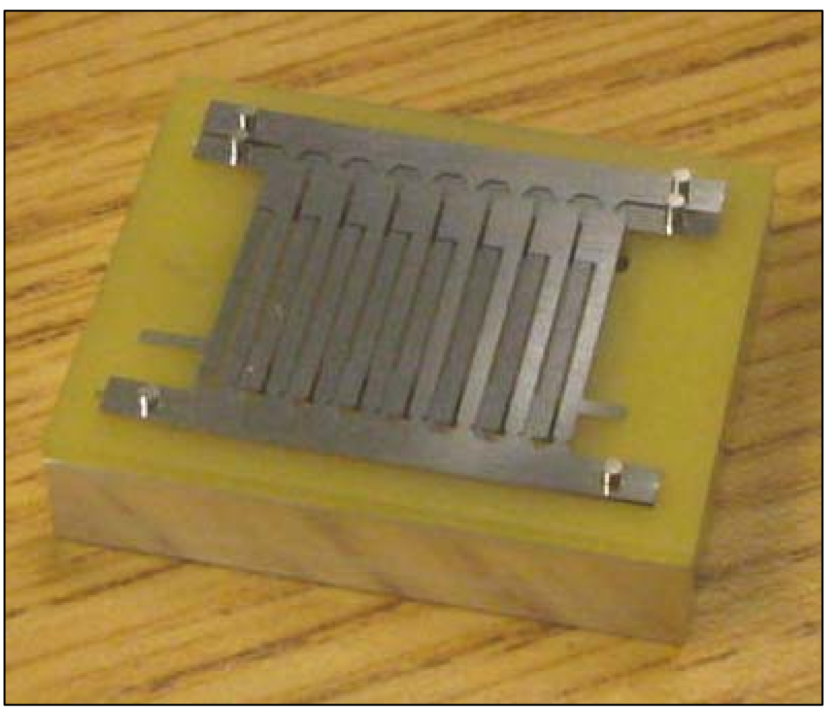

Figure 9. Practice parts (300 series stainless steel) on spot welding fixture.

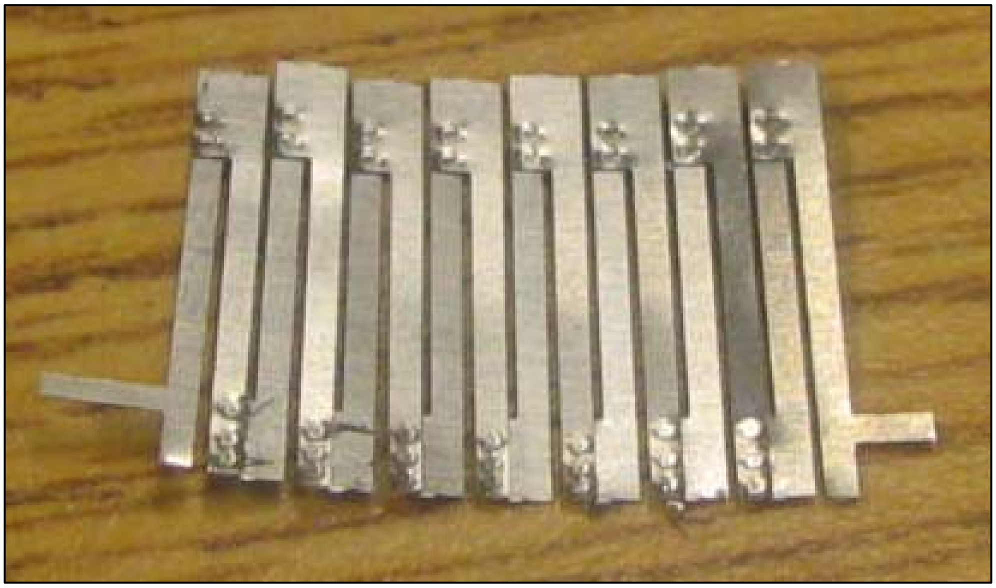

Figure 10. One strip of 15 couples after spot welding (practice parts).

Following confirmation of fabrication and assembly methods and receipt of all actual demonstrator parts, the demonstrator and its supporting fixtures were assembled. For the subsequent testing of the demonstrator, various configurations of the demonstrator and supporting equipment were used. As the tests are described, the demonstrator configuration will be presented.

Summary of Testing Conducted

a. Test 0: Test the Chromel-Constantan eight couple TEG element without airflow, no convection, to confirm that the behavior of the couples is consistent with published data.

b. Test 1: Test the TEG holding the hot and cold sides at constant temperatures and identify the influence of convective flow on TEG performance.

c. Test 2: Test the TEG holding the hot side temperature constant, not controlling cold side temperature, and identify the influence of convective flow on TEG performance.

d. Test 3: Test the TEG using a DC power source, holding the hot side temperature constant during open circuit conditions, but allowing it to fluctuate as power is drawn from the TEG. The cold side temperature is not controlled. Identify the influence of convective flow on TEG performance.

Convective TEG Components and Test Assembly

For the testing conducted, a single strip consisting of eight Chromel-Constantan TE couples in series, Figure 10, was fabricated and functions as the TEG. Figure 11 shows the assembled cold side TEG housing and illustrates the water and air flows of the unit. Figure 12 shows the test assembly with the hot side exposed.

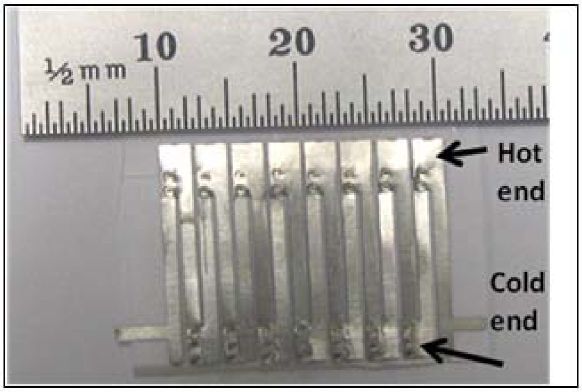

Figure 11. A single strip of Chromel-Constantan TE couples, eight in series.

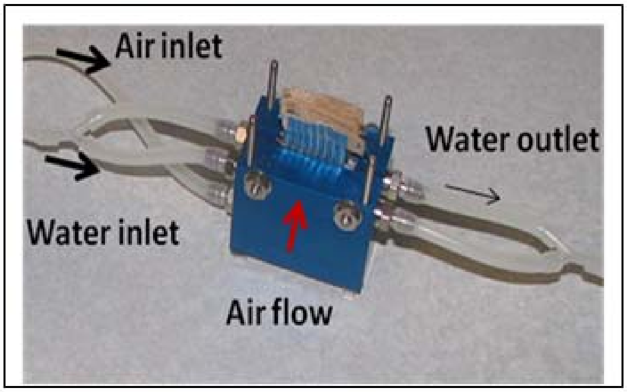

Figure 12. Cold side housing, illustrating water and air flow paths.

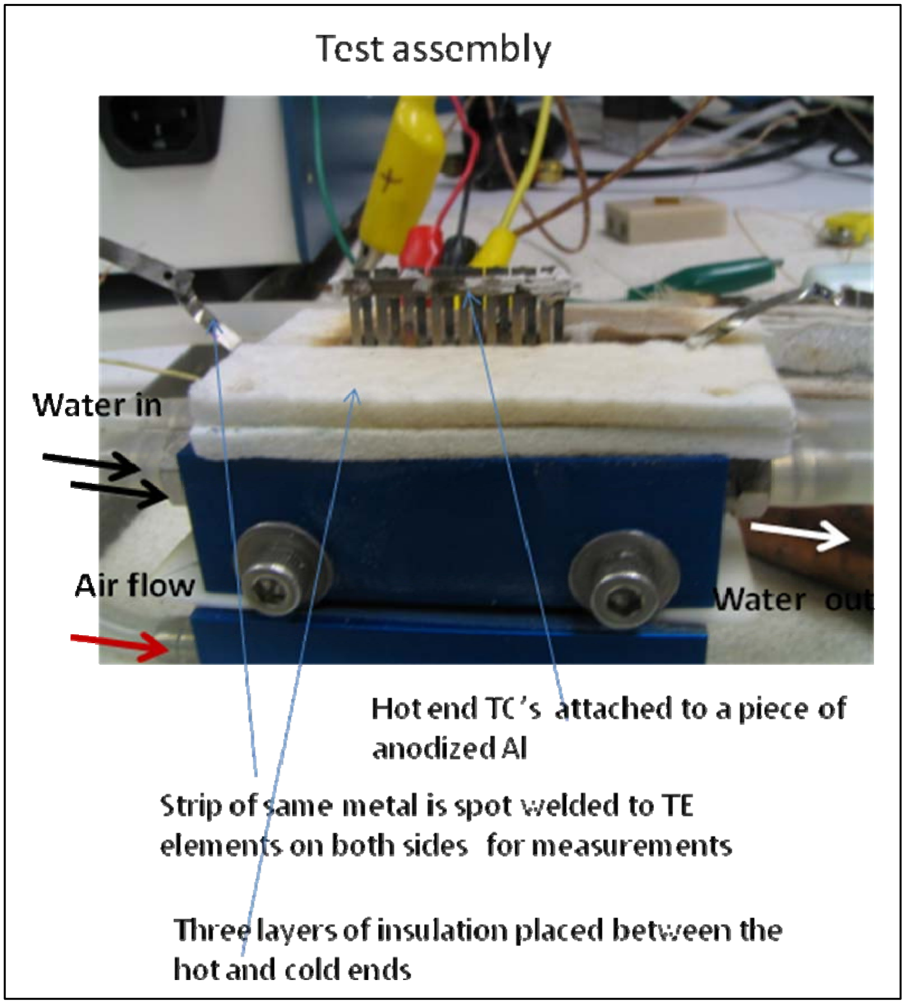

Figure 13. Test assembly with hot side configuration exposed.

Once the demonstrator was determined to be ready for testing, Tests 0 through 3 were conducted, test data was captured and analyzed, and conclusions were drawn where appropriate. Test details are presented below.

Test 0

Objective: Confirm that the behavior of the Chromel-Constantan eight TE-couple strip is consistent with published data, confirming its expected performance during subsequent testing.

To carry out this test, heat will be supplied to the TEG hot side by two cartridge heaters, while heat will be removed from the cold side a water flow. No air flow will be present, as it facilitates the convective effect when present. There is to be no possibility of a convective effect as being studied during this test. The data to be generated will be compared to published values. To ensure compatibility, no convective effect is to be at work when the data is generated.

The configuration of the test assembly is shown in Figures 13, 14, 15, and 16 below.

Figure 14. Instrumented Chromel-Constantan TEG strip.
Two thermocouples are attached at the hot side and two are attached at the cold side. One thermocouple at each end is spot welded to the strip and another is glued.

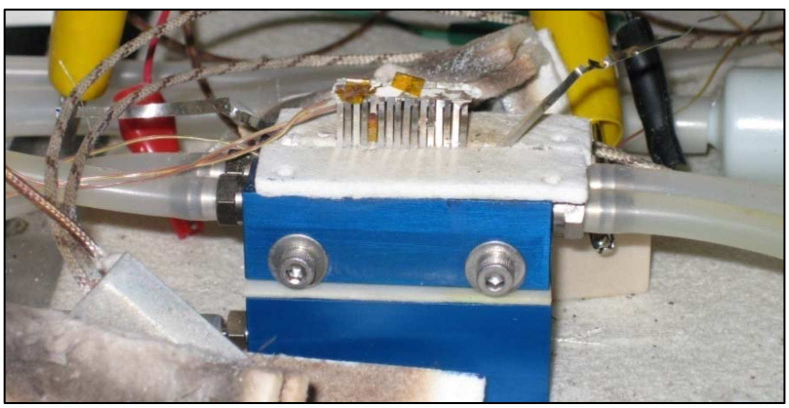

Figure 15. Strip assembly in the test fixture.
The cold side of the TEG strip is held between two anodized aluminum plates. Air flows from the bottom housing through the cold side of the TEG and escapes into the atmosphere from the hot side.

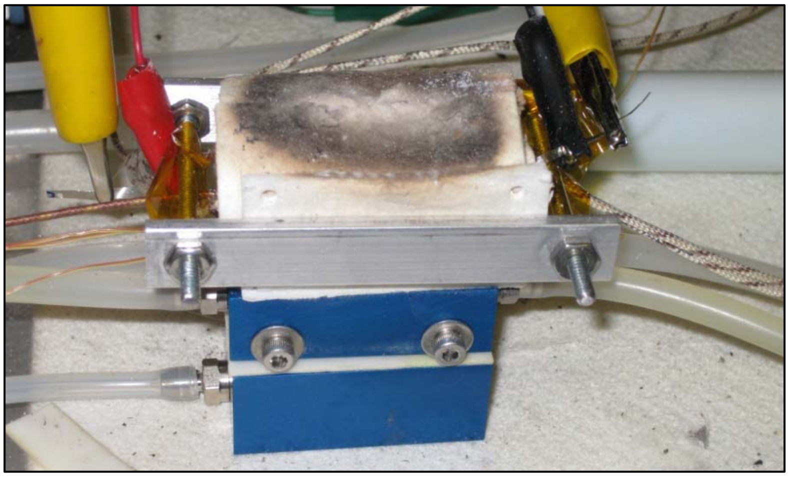

Figure 16. Fully assembled test fixture with cartridge heaters inserted.
One cartridge heater is placed on each side of the TEG strip. Each heater is wrapped in thermal insulation on its three sides that are not exposed to the TEG. The heaters and insulation are held together and in place by a clamp fixture.

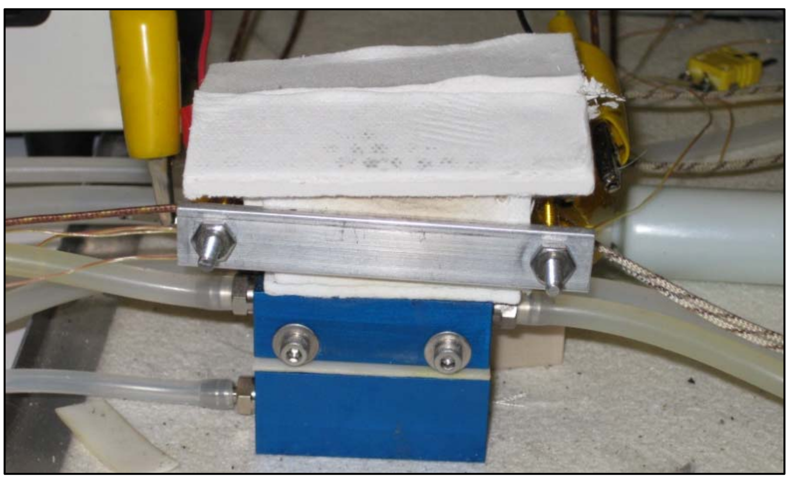

Figure 17. Test fixture illustrating clamp holding cartridge heaters and insulation.

Results.

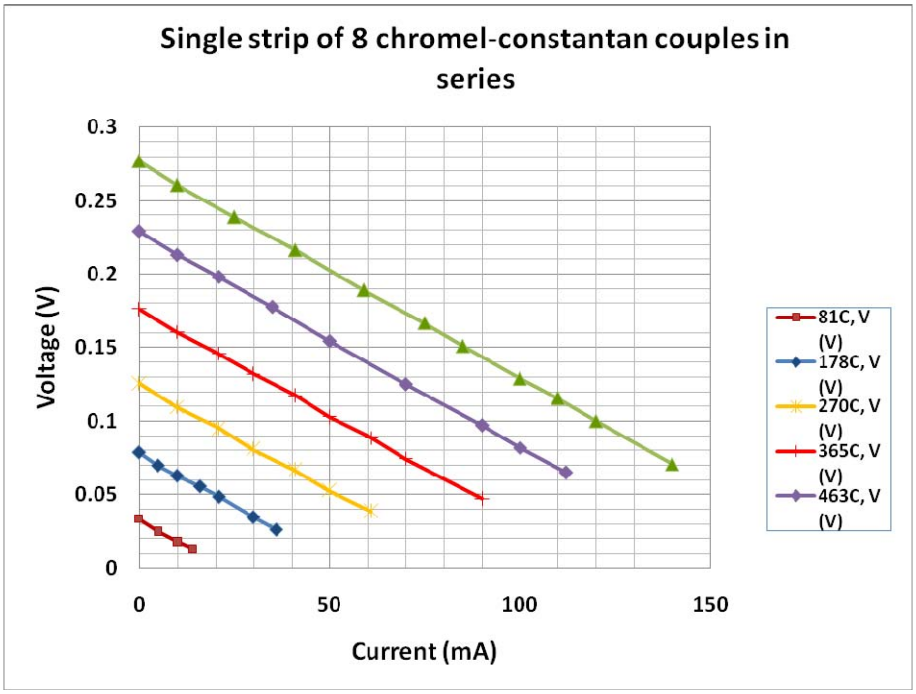

Figure 18. No air flow test results.

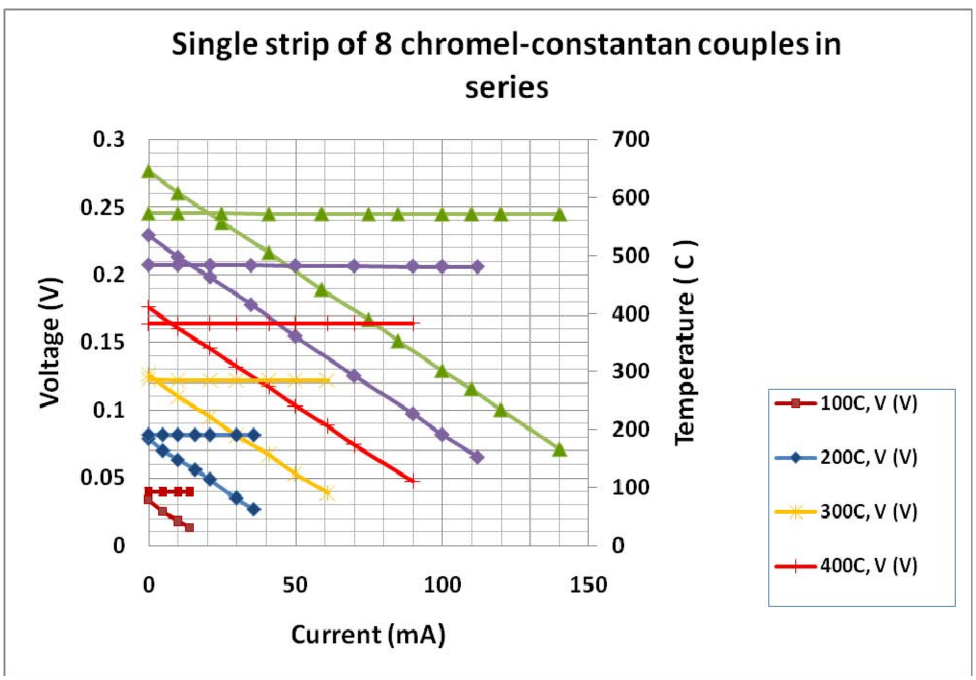

Figure 19. No air flow test results.

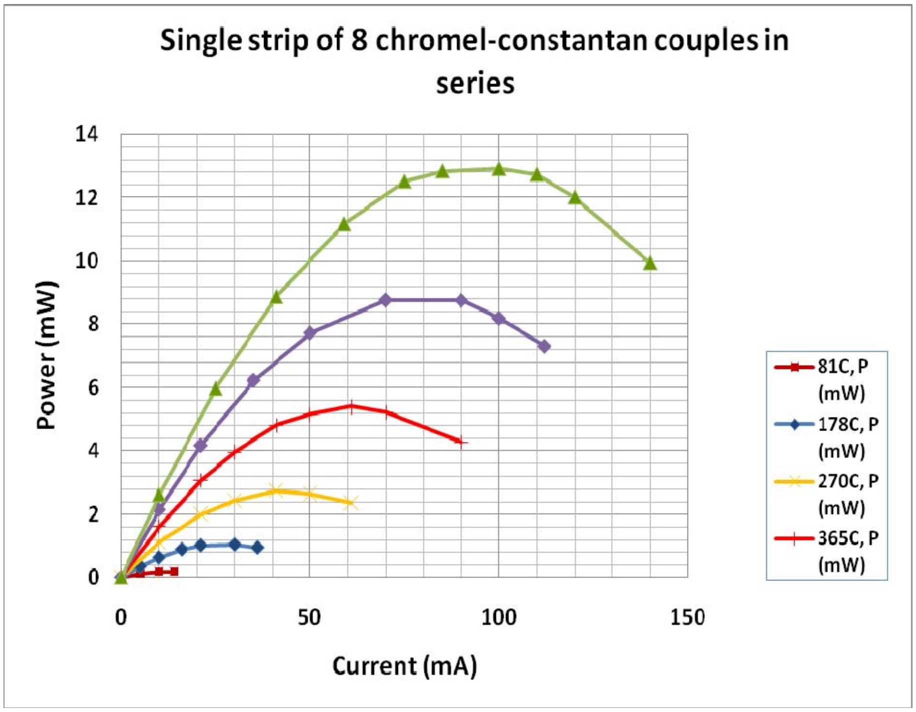

Figure 20. **Illustrates that temperatures are held steady during no air flow test results.**

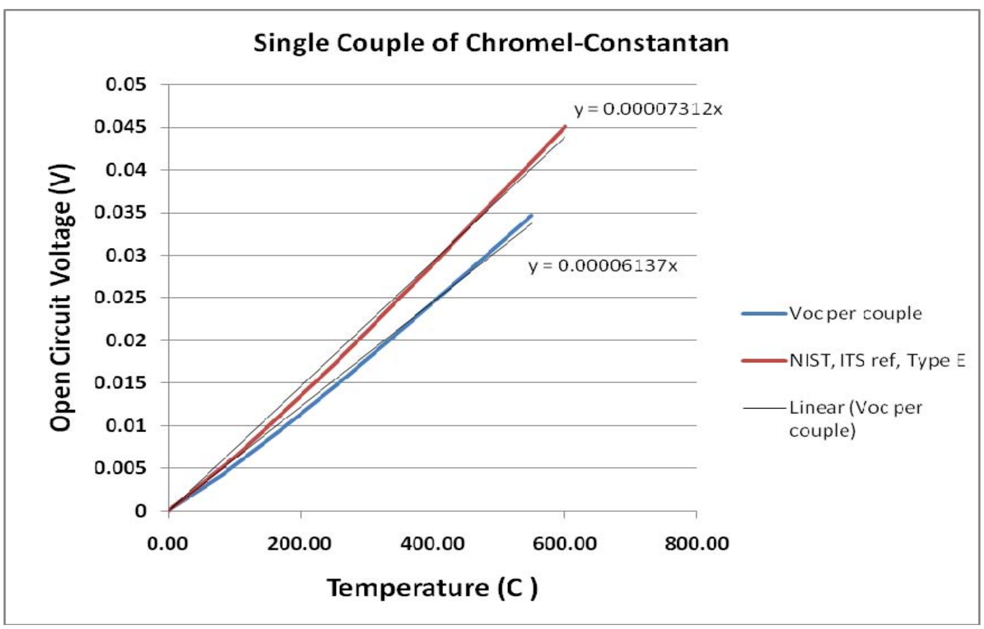

Figure 21. **Linear fit to the data shows that output voltage per Chromel-Constantan couple is approximately 61uV/deg C.**
This value correlates well enough to published values to provide confidence in the behavior of the couples used in this series of testing.

Test 1

Objectives: Test conditions for Test 1 were to hold constant the temperatures of the hot and cold sides of the TEG while studying the influence of convective air flow on TEG performance.

Results.

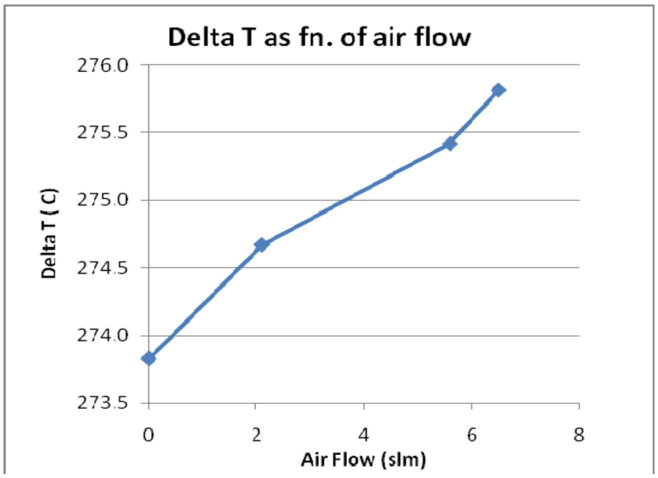

Figure 22. Influence of airflow on Delta T.

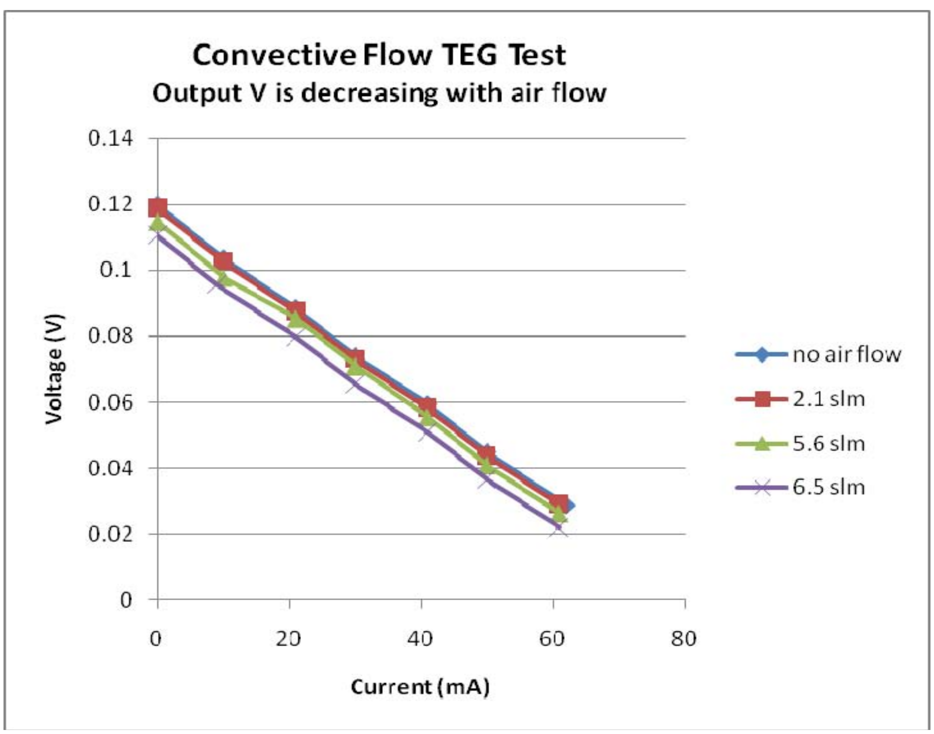

Figure 23. Influence of convective air flow on output voltage.

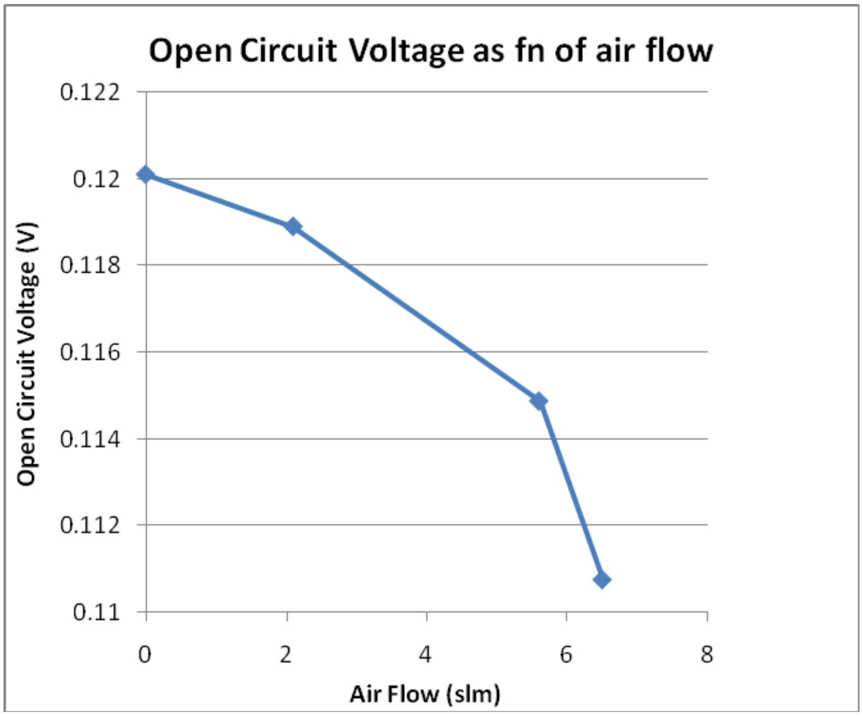

Figure 24. Influence of convective air flow on open circuit voltage.

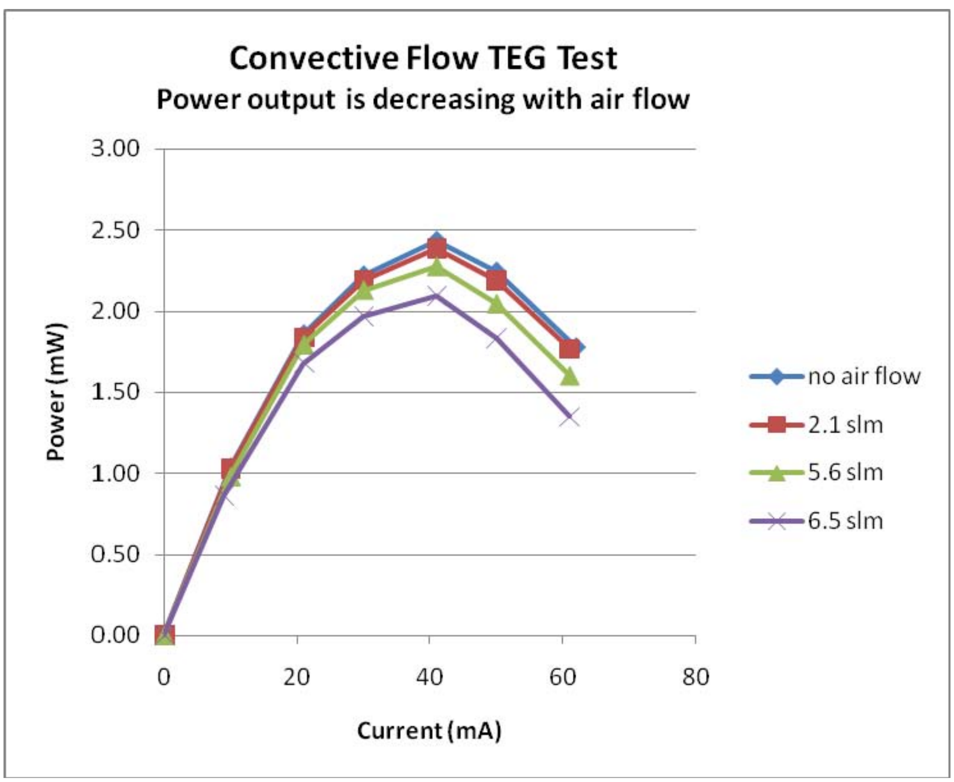

Figure 25. Influence of convective air flow on power output.

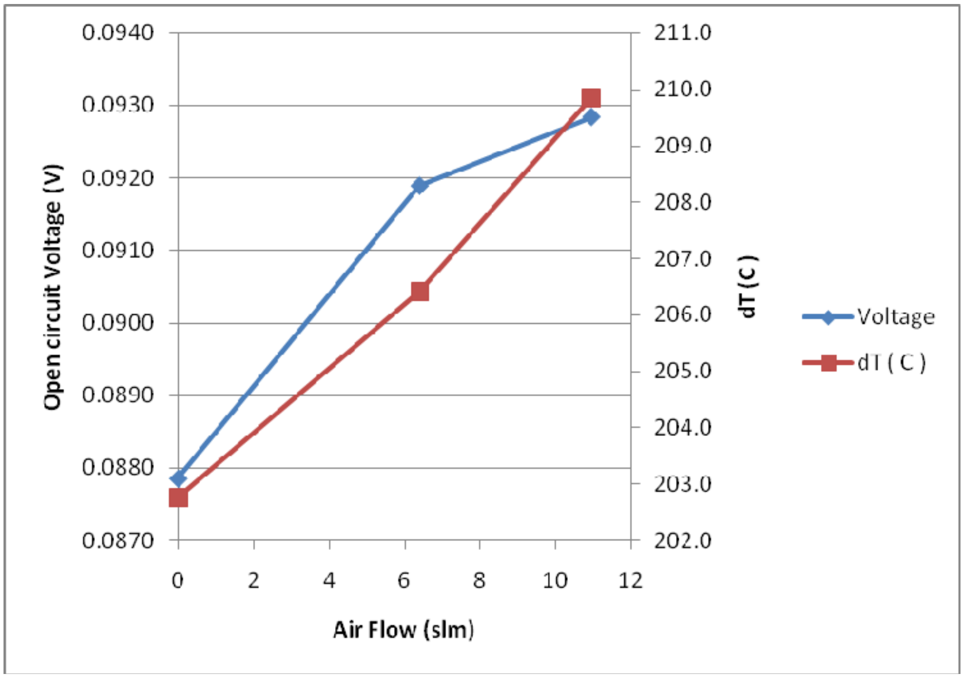

Figure 26. Influence of convective air flow on open circuit voltage.

Observations.

When convective air flow is present, both cold side and hot side temperatures decreased. Experimental conditions were not suitable to keep the cold side at the target temperature by modifying the cold side heat sink. Similarly, the hot side heat sink requires modification to keep operating conditions steady. Because of all of these compounding effects, several experiments were designed to allow the influence of convective air flow to be clearly identified. Experimental test conditions with several boundary conditions to characterize the effects of convection on performance were conducted subsequently.

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Test 2

Objective: The conditions for Test 2 were to hold the hot side of the TEG constant, but to not control cold side temperature while studying the influence of convective air flow on TEG performance.

Results.

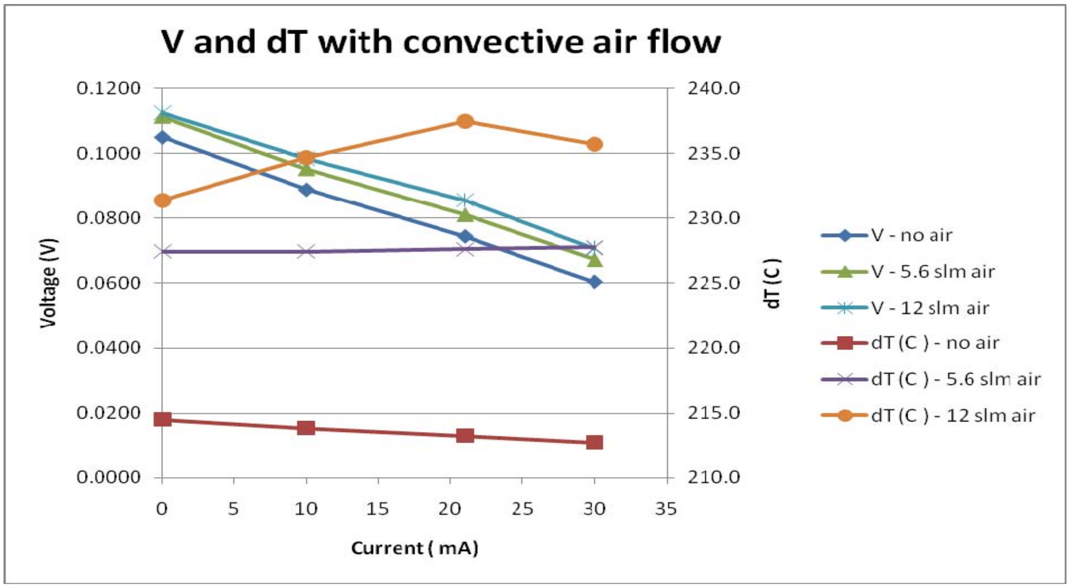

Figure 27. Influence of convective air flow on voltage and delta T.

Observations. Results show that the open circuit potential as well as the delta T are increasing with air flow. Since the hot side temperature is held constant, all the delta T change is coming from the decrease in cold end temperature with air flow. With convective air flow, both the hot side and cold side temperatures of the TEG are decreasing. However, in this experiment, the cartridge heaters were maintaining a constant hot side temperature at all air flow points, while the cold side is allowed to respond to the air flow conditions. These results show that the convective flow of air is decreasing the effective thermal conductivity of the TEG and increasing the delta T and voltage output as expected. However, when power is drawn from the TEG, due to the Peltier effect, the hot and cold side temperatures change, and the temperature controller adds extra power to keep the hot side at a constant temperature.

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Test 3

Objectives: The conditions for Test 3 were, using a DC power source, to hold the hot side temperature constant during open circuit conditions, but allow it to fluctuate as power is drawn from the TEG. The cold side temperature is not controlled.

Results.

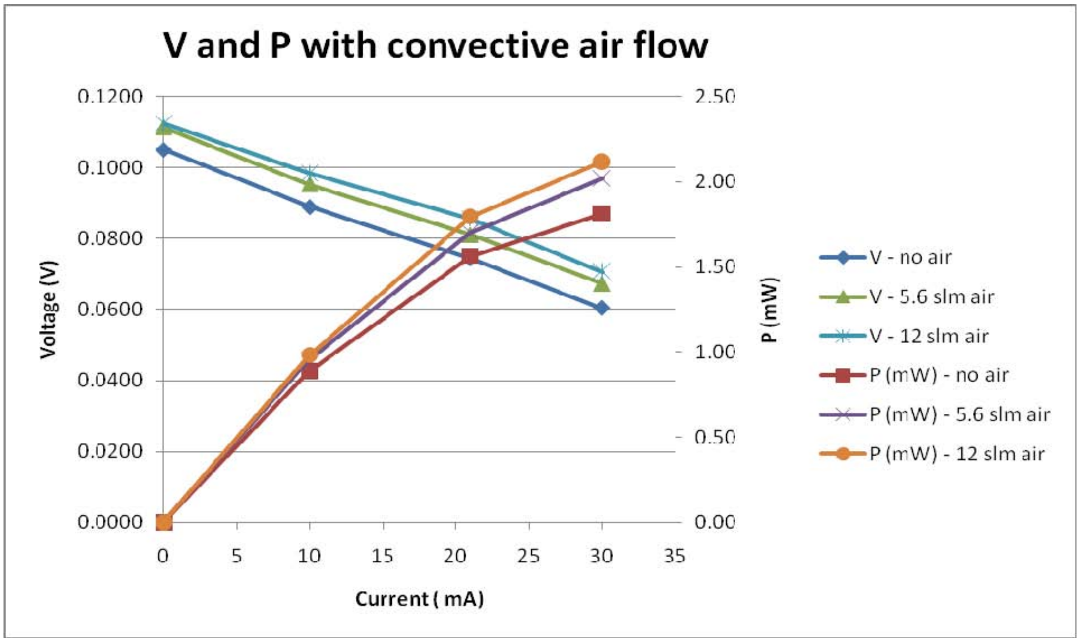

Figure 28. Influence of convective air flow on voltage and power.

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Chromel-Constantan TEG (8 couples in series) performance with convective air flow

Air flow (slm)	Th (C)	Tc (C)	dT (C)	V (V)	I (mA)	P (mW)	% incr. in TEG power output	DC power (W)	% incr. in DC power input
0	265.8	51.3	214.5	0.1051	0	0.00		9.24	
0	265.8	52.0	213.9	0.0889	10	0.89		9.24	
0	265.8	52.5	213.3	0.0744	21	1.56		9.24	
0	265.8	53.1	212.8	0.0604	30	1.81		9.24	
0	265.8	53.7	212.1	0.0446	42	1.87		9.24	
5.6	265.3	37.9	227.4	0.1115	0	0.00	0.0%	10.56	14.3%
5.6	265.3	37.8	227.5	0.0955	10	0.95	7.4%	10.56	14.3%
5.6	265.5	37.8	227.6	0.0812	21	1.71	9.1%	10.56	14.3%
5.6	265.7	38.0	227.7	0.0674	30	2.02	11.5%	10.56	14.3%
12	264.0	32.7	231.4	0.1125	0	0.00	0.0%	15.13	63.7%
12	267.5	32.8	234.7	0.0983	10	0.98	10.6%	15.13	63.7%
12	271.3	33.8	237.5	0.0856	21	1.80	15.0%	15.13	63.7%
12	269.3	33.6	235.7	0.0707	30	2.12	17.0%	15.13	63.7%

Table 2. TEG (8 couples in series) performance with convective air flow.

Observations. The test conditions established for Test 3 allow measurement of the influence of convective air flow on TEG performance. Test 3 shows an increase in TEG performance with convective flow, as noted in Figure 19. As noted previously with increased air flow, both hot side and cold side temperatures drop. DC power supply power input was increased to compensate for the drop in temperature with air flow under open circuit conditions. Under open circuit conditions, DC power input to the system was adjusted to maintain the hot side temperature of the TEG at a constant temperature of 265°C. No power adjustments were made to compensate for the Peltier effect. DC power was not adjusted for a drop in TEG temperature with current flows.

Summary and Conclusions

1. Conditions required to isolate the effect of convective air flow: To measure the influence of convective airflow on TEG performance, the test conditions must be modified to allow the hot side and cold side temperatures of the TEG to change with air flow without external system changes. Do not hold the cold temperature constant with a constant temperature bath. Do not compensate for temperature drops in the TEG at the hot and cold sides due to Peltier effect. With air flow, both hot and cold side temperatures change. Air flow tends to cool both sides. However, to see the beneficial influence of convective air flow on the TEG, the air flow should be such that it should not cool the hot side. In other words, the heat source should be big enough so that small convective air flows will not reduce the hot side temperature of the TEG. In the current set of experiments, the heat input to

the hot side of the TEG is increased to compensate for the drop in temperature that would otherwise occur with air flow.

2. Realizing the benefit of convective air flow: Efficiency improvements gained through the application of convective air flow will be apparent only with a TEG where the heat source is big enough to be unaffected by small convective air flows, and where the energy consumption for the air flow is small or can be freely utilized from the system without a negative effect.

3. Additional characterization of the benefit of convective air flow: More comprehensive understanding of the benefits of convective air flow could be obtained by conducting additional experiments under a much wider range of conditions than were used in this initial characterization effort. This additional characterization could readily be carried out using the metallic element TEG demonstration device design. Testing with a thick film device would provide characterization of improvement in performance of such a device, but would be expected to provide similar order of magnitude benefit to performance as that seen with the metallic element device. Thick film testing would confirm earlier results, but was primarily intended to explore what absolute level of performance could be achieved with a thick film device using convective air flow, as the thick film would be in a relatively untested state, just emerging from development.

Determine of Program Completion

It was jointly concluded by the program officer and BSST that there was much diminished benefit to further experimentation at this point. Funding remaining would only facilitate very limited further experimentation. As a result, it was determined that no further work would be performed. The results achieved demonstrated that a limited benefit could be obtained from the use of convective air flow in a TEG under certain conditions. This suggests that convective air flow might be incorporated into future TEG designs where the scale of the TEG was large enough so that the limited percentage performance gain provided by convective air flow would still result in a meaning increase in the power output of a field-deployed TEG. Should TEGs develop to this state, further characterization of convective air flow’s benefit to TEG performance may be warranted.